CREATING KISS-BONDS FOR NON-DESTRUCTIVE INSPECTION

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ABSTRACT

A novel method for creating kiss-bonds within a composite structure is presented. Kiss-bonds are a defect type whereby there is a loss of structural continuity within the material, yet the material remains in intimate contact across the defect. This results in a local loss of strength, which can then develop into a serious structural issue under in-service loads. With lightweight structures being at a premium for performance and emissions considerations, ensuring that a composite structure is both optimised and safe is a priority. This requires a thorough knowledge of the structural implications of kiss-bonds, as well as an ability to detect and characterise kiss-bonds in structures. Satisfying these requirements has been hindered by the difficulty in manufacturing – in a controlled, repeatable manner – test panels that contain representative kiss-bonds, for mechanical characterisation and Non-Destructive Inspection (NDI). In addition, there is currently no method to reliably detect kiss-bonds within repair bond-lines, directly hindering the design of bonded repairs. Kiss-bonds are therefore impeding the optimisation of composite structures and repairs.

The method presented in this work addresses these issues by creating controllable and repeatable kiss-bonds for scientific interrogation. Areas of two adjacent plies are pre-cured before being incorporated within a laminate and autoclave cured. Following consolidation, no bonding occurs between the pre-cured areas. The robustness of the technique – in terms of repeatedly creating kiss-bonds – was evaluated via ultrasonics and laser shearography.

1 INTRODUCTION

Advanced composite materials have become increasingly popular in high-performance structural applications due to their favourable weight, strength and fatigue characteristics. With increasing focus on reducing greenhouse emissions through a reduction in fuel consumption and an increase in renewable energy, composite materials are now being used in large-scale primary structures. For example, the latest generation of jet transport aircraft, such as the Bombardier C Series, Boeing 787 and Airbus A350, make extensive use of Carbon Fibre Reinforced Polymer (CFRP) in both the wing and fuselage. Likewise, composite materials are being used in both the spar and skin of wind turbine blades, facilitating larger blades to harvest increasing amounts of energy from the wind [1,2].

The shift in use of composites towards safety-critical, load-bearing structures requires further development of damage detection and assessment capabilities. Damage can occur in composites due to an impact or loading event, environmental exposure or as a manufacturing defect. This can lead to sub surface delamination, dis-bonding, and/or fibre breakage, with little or no evidence of these damage types being visible on the surface [1,2]. Advanced Non-Destructive Inspection (NDI) techniques are therefore required to scan, detect and assess the damage to guarantee sufficient structural integrity. Should a repair be required (such as a bonded patch), NDI can then be used to assess the quality of the bondline post repair, which can be hidden from view. Several NDI techniques are available, each with their own pros and cons for detecting particular damage types or for a particular composite structures [2]. However, it is acknowledged by the Federal Aviation Administration (FAA) that current NDI techniques are not sufficiently capable of detecting kiss-bonds, which is directly impacting on the use of composites in primary structures [3]. If kiss-bonds could be reliably detected, manufacturers would not need to be as conservative in the design of composite structures, leading to lighter and thus more efficient aircraft.

Kiss-bonds are a defect type that is of critical concern to the aerospace industry. They can be defined as a type of defect in which two surfaces within the structure are in intimate contact; with no bonding existing between the two surfaces, (i.e. no structural continuity is present). This leads to a reduction in the load-carrying capabilities. A similar defect to this is a weak-bond, where there is inadequate bonding between two surfaces. A weak-bond may be much more difficult to assess as there is some element of structural continuity. Such defects can occur within monolithic, sandwich, bonded or repaired composites, and can be introduced during manufacture, or as a result of damage or inadequate repair. The loss in structural strength, along with the potential growth of the defect under in-service loading conditions (i.e. grow from a weak-bond/kiss-bond into a dis-bond), makes detection and assessment of this defect type particularly important. However, the physical characteristics of the defect (i.e. sub-surface, within bond-lines) make it challenging to detect [1-2,4].

Although many NDI systems are described as being capable of detecting kiss-bonds (e.g. ultrasonics [2,4], laser shearography [2,5,6], percussive diagnostics [7] and laser bond inspection [7,8]), the true abilities and limitations of these systems are unknown. This is, in part, due to the difficulty to directly create kiss-bonds in a controlled fashion for interrogation by NDI systems (i.e. controlling location, size and shape of the defect). Current approaches to create test panels for NDI evaluation or equipment calibration often involve a film insert. This is not fully representative of a true defect and, moreover, can work to the strengths/weaknesses of a particular NDI system, providing misleading results.

The inclusion of another material into the structure can give misleading NDI results. Table 1 describes the operating principles of NDI techniques that could be used to detect kiss-bonds in composite structures. Each system relies on a different defect characteristic for the purposes of damage detection. Film insertions simulate a kiss-bond by creating a structural discontinuity. However, insertions are a defect type themselves, and thus introduce other characteristics that can be more readily detectable by NDI systems. For example, does an ultrasonic scan detect the simulated kiss-bond or the interface between the film insertion and the surrounding material? Likewise, thermography might detect the change in conductivity caused by the film insertion. Therefore, using film insertions for the purposes of assessing NDI systems capabilities of detecting kiss-bonds may lead to very misleading results.

System	Operating principle	Defect characteristic detected
Ultrasonics	Monitoring reflection of sound waves travelling through the thickness of a component	Surface-interface created by the defect
Laser Shearography	Monitoring local alterations to surface strains following mechanical loading	Change in local stiffness caused by the defect
Thermography	Monitoring surface temperature gradients during a temperature change	Local change in thermal conductivity caused by defect
Radiography	Monitoring x-rays absorbed by component	Change in density at the defect

Table 1: Operating principles of popular NDI systems

Contaminants have also been used as means of replicating kiss-bonds (which is also a defect type in itself). However, the use of contaminants limits the repeatability and control (in particular, the shape of the defect) of the process. In relation to characterisation of the defects effect on load carrying capabilities, what is ultimately of interest is the ability to link an NDI result to degradation in structural performance. This requires a repeatable and controllable technique that is flexible in terms of size and defect location.

The goal of the work undertaken was to develop a method of directly creating kiss-bonds within a composite structure and to assess the abilities of selected NDI systems at detecting these kiss-bonds. In this study, the cure cycle of the composite material was manipulated to create areas with zero inter-lamina bonding within monolithic panels. Subsequently, a number of NDI techniques, namely ultrasonics and laser shearography, were used to inspect/assess the created defects.

2 METHODOLOGY

The method of creating defects involves 'pre-curing' discrete areas of two adjacent plies before incorporating these plies into a laminate, which is then be cured as per normal practice. The manufacturing process must be tightly controlled in terms of surface finish and degree of cure; otherwise another defect type may be produced (e.g. a dis-bond or a weak-bond). The surface finish must be smooth and flat to maintain intimate contact throughout the entirety of the pre-cured areas. Secondly, the pre-cured areas must undergo a complete cure prior to the laminate cure cycle. Otherwise, bonding can occur across the defect leading to some structural continuity. Lastly, the edges of the pre-cured areas need to be well defined, so that there is a clear boundary to the area of the created defect (i.e. not a gradual transition from uncured to cured material).

The irreversible cure properties of a thermosetting epoxy matrix was exploited in this case to guarantee that no further curing (and thus bonding) occurs between the pre-cured areas during the laminate cure cycle. The pre-curing of the material used an electrically powered heating element attached to an aluminium block. The block features the desired defect shape extruded from the bottom surface. The heating element is mounted on the top surface of the block, transferring heat into the block by conduction. This heats the extruded defect shape, which is placed in contact with the CFRP material (see Figure 1 for an exploded view of the apparatus).

The heat applied must be precisely controlled to ensure that the defect area undergoes complete cure while the surrounding area remains uncured. This requires that the heat remains localised and does not flow to the surrounding material. Control of the heat is accomplished by partitioning the tool-plate so that the area directly under the material being cured is separated from the surrounding tool-plate by an air gap. This is shown by the insulation block in Figure 1. The insulation block is identical to the defect shape extruded from the aluminium stamp.

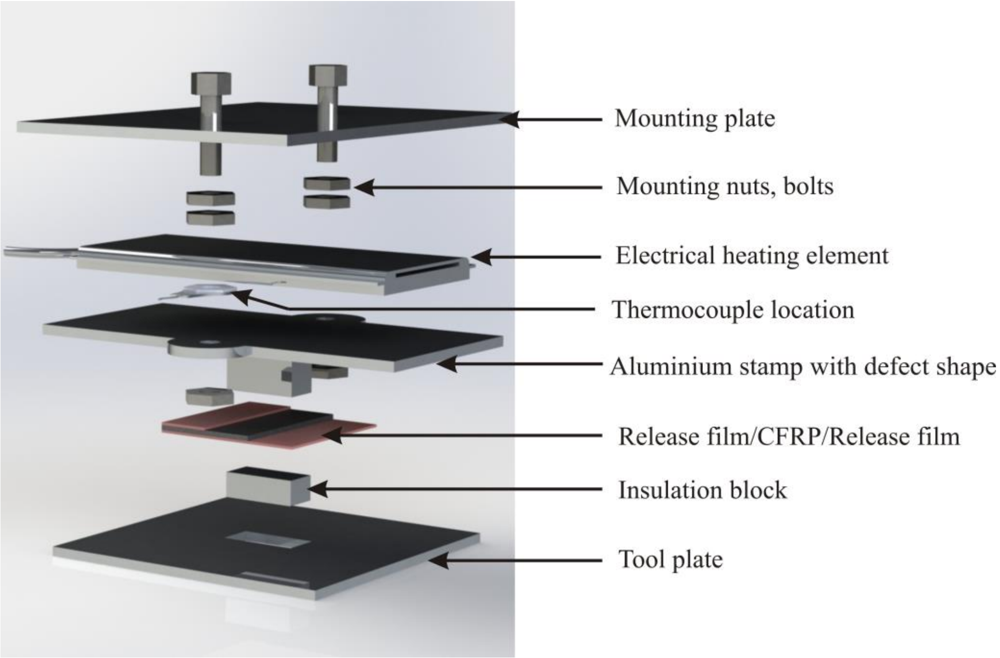

Figure 1: Exploded view of equipment used to pre-cure areas of individual plies

The location of the pre-cured areas on these two plies must be identical so as to ensure that they align correctly when the two plies are stacked. A mount is used for the electrical heater/stamp assembly. The mount attaches to the tool-plate, locking its position in relation to the insulation block, which defines the defect area. In order to provide a flat and smooth surface finish, the ply being prepared is placed under a vacuum bag, with release film being use to keep the ply clean and to keep it from bonding to the tool-plate.

The method now requires that a temperature, ramp rate and cure time be defined. A thermocouple was used to monitor the temperature and control the output of the heating element. Obtaining a temperature reading at the ply is not possible, as introducing a thermocouple at this location would leave an imprint on the ply’s surface. Therefore, the thermocouple was mounted at the electrical heating element (see Figure 1 for the precise location). The temperature reading at this location does not provide the material (and thus the curing) temperature – so the set point and dwell time had to be tuned to ensure a full cure. This was accomplished by choosing a temperature set-point, and altering the dwell time until Differential Scanning Calorimetry (DSC) analysis showed no further cure of the material was possible.

3 PANEL MANUFACTURE

The material chosen for the study was Hexel HexPly® 8552, which consists of biaxial carbon fibres pre-impregnated with a thermosetting epoxy matrix (cure temperature of 180°C). All laminates manufactured were 8 plies thick ($[0/90_2/0]_s$ stacking sequence), with areas of the two mid-plies pre-cured to create kiss-bonds. Five panels (dimensions shown in Figure 2) were manufactured with kiss-bonds to verify the method. Following the lay-up process, the panels were autoclave cured as per the manufacturer defined curing cycle (7 bar pressure and hold at 180°C for 120 min). No cutting or trimming took place following the cure, to ensure that the defects were not agitated, potentially forcing the defect to grow into a dis-bond.

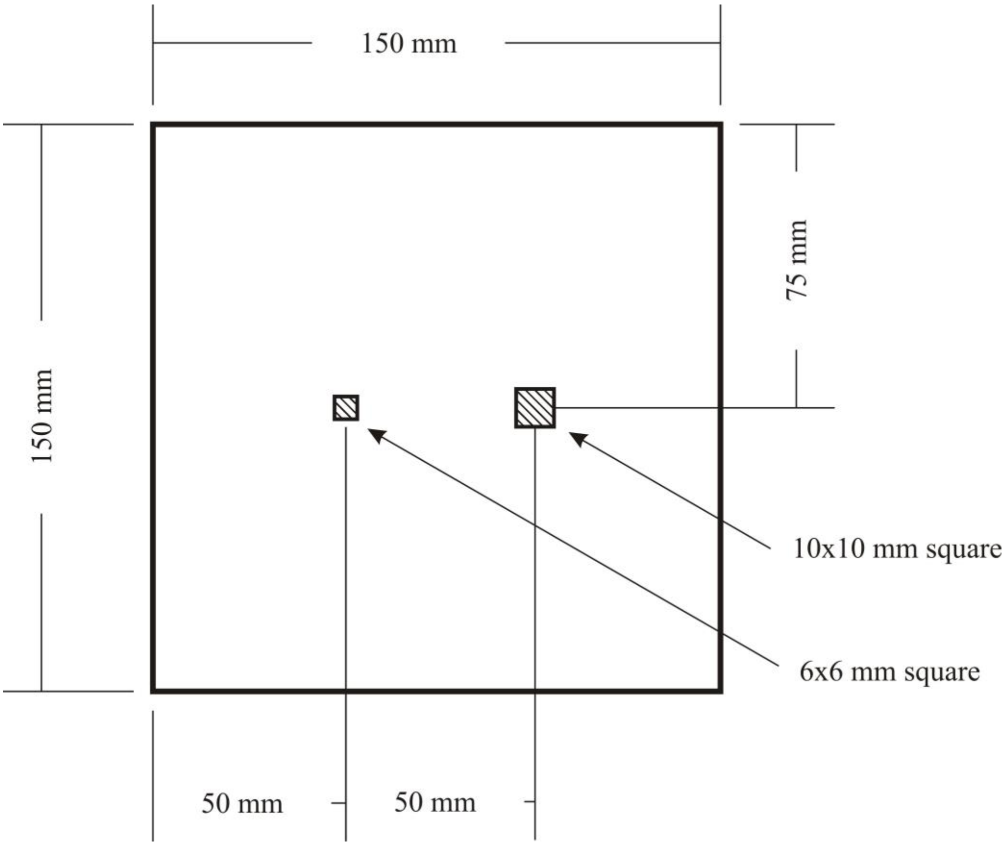

Figure 2: Dimensions of the panels produced, showing the kiss-bond area locations

4 RESULTS

A visual assessment of the manufactured panels gave no indications of the existence of any sub-surface defects. No ridges, lips or other perturbations could be seen or felt on the surface above the defect areas. The defects were analysed with both ultrasonics and laser shearography NDI systems.

The two systems were evaluated in terms of their ability to detect defects, and their ability to determine the defect type.

Ultrasonic evaluation was conducted using a GE Phasor XS system with a phased-array roller probe, pictured in Figure 3. A combination of A-, B-, and C-scan were used to detect and characterise the defects. Using water as a couplant, all defects were readily detected using ultrasonics.

Figure 3: GE Phasor XS with a phased-array roller probe

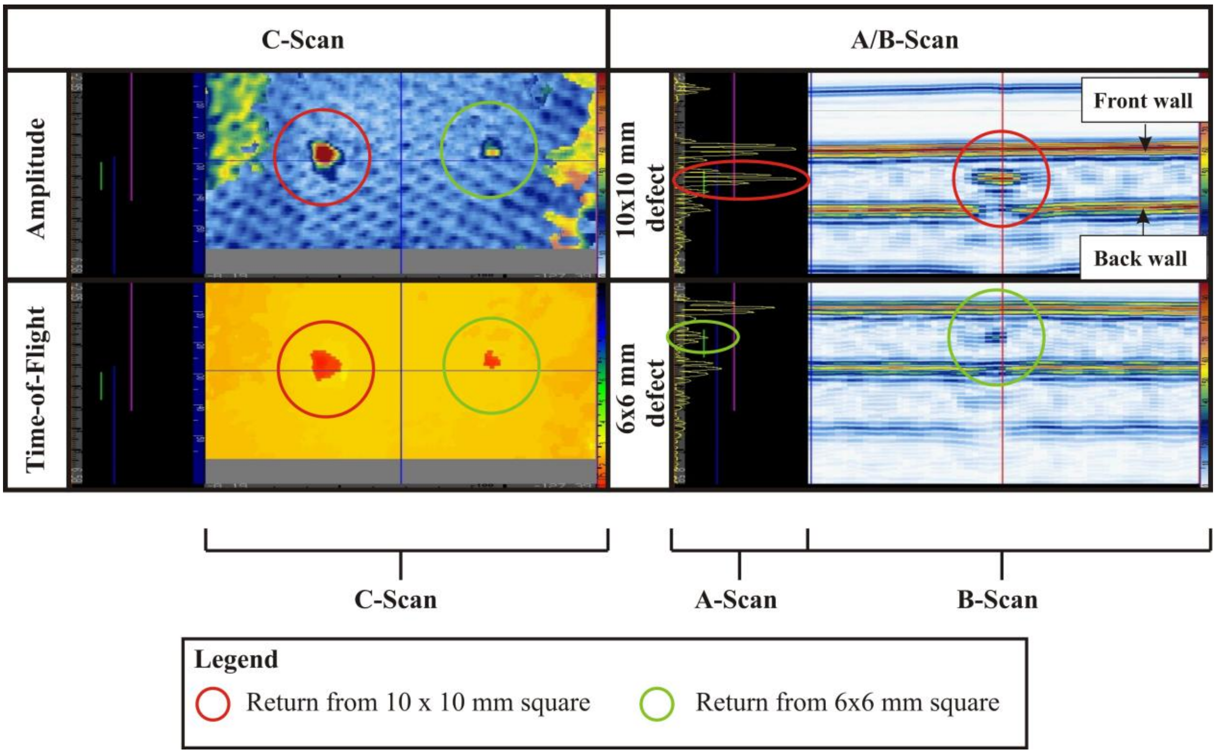

Figure 4: Typical ultrasonic result (example given from panel 1)

The system was first calibrated on a panel which did not contain any defects. The interference, amplitude, and time-of-flight gates were then set appropriately. These are indicated as the purple, green and blue vertical lines respectively in the A-Scan in Figure 4. The amplitude gate was set so that it would be triggered by any defect within the panel, while remaining uninfluenced by the front and back walls. Finally, the time-of-flight gate was adjusted so as to be triggered by anything after the front wall to below the back wall.

Using this technique, the nature of the defect (i.e. kiss-bond or dis-bond) could be determined, by monitoring the back-wall echo directly under the defect using a combination of the A- and B-scans. As the defect is detectable, it is – by definition – reflecting a portion of the sound energy and stopping it from reaching the back wall, and thus a reduction in the return from the back wall is expected. In the case of a dis-bond, the significant portion of the signal will be returned from the defect (due to the presence of air), resulting in a clear and significant break in the back wall. In the case of a kiss-bond, the majority of the signal passes through the defect unabated. This results in a relatively weak return from the defect, while giving a strong and continuous return from the back-wall under the defect. As this particular ultrasonic system is contact based, great care must be taken to ensure that the operator doesn't apply too much pressure and effectively close the defect.

It can be seen in the ultrasonics result of panel 1 (shown in Figure 4) that both defects were detectable by C-Scan (both amplitude and time-of-flight). The A-/B-scan of the 10 x 10 mm square shows that the defect breaks the back wall completely, indicating that in this instance a dis-bond was created. On the other hand, a kiss-bond is detected by monitoring the back wall echo and amplitude gates of the 6 x 6 mm defect; a clear distinction can be made between this defect and that of the 10 x 10 mm defect. Use of time of flight data can be used in support of this.

A summary of the remaining ultrasonic results is shown in Figure 5. Each defect has been assessed thoroughly and categorised. In total, 7 defects have been categorised as kiss-bonds, with the remaining 3 categorised as dis-bonds. This result indicates that all defects could be found and 70% of them are considered to be kiss-bonds.

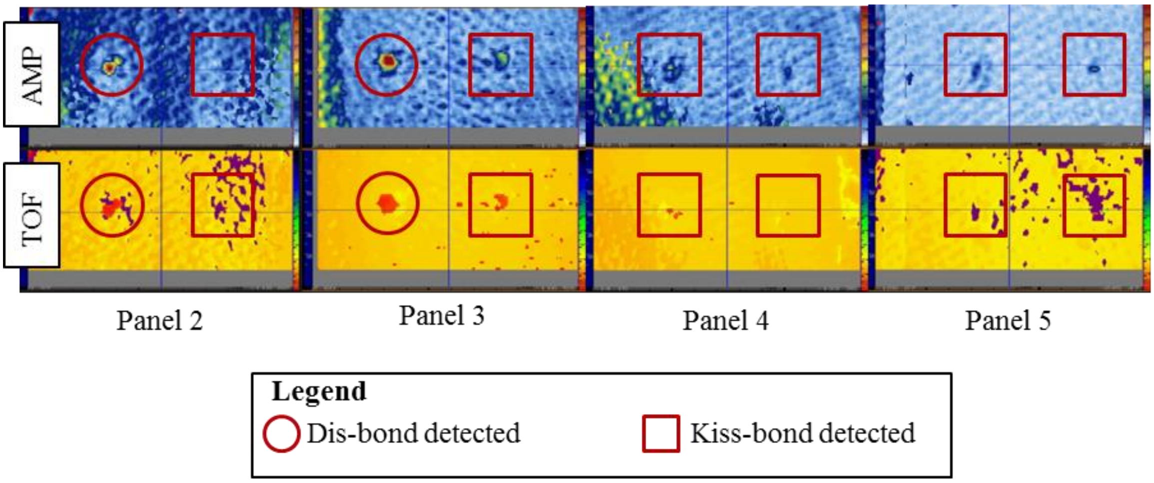

Figure 5: Ultrasonic C-scan results of panels 2-5. The amplitude (AMP) result is shown on top with the time-of-flight (TOF) result underneath. Dis-bonds are denoted as circles, kiss-bonds are denoted by squares.

Laser shearography was also used to detect and analyse the defects. A Defect Dtect system manufactured by Laser Optical Engineering Ltd. was used. Shown in Figure 6(a), this system consists of an illumination module (DDIM-150) and an imaging module (DDSM-15). The illumination module contains a class 2M laser with a wavelength of 532 nm. The imaging module contains a CCD camera with image resolution of 1280x1024 and a frame rate of 25 fps.

The specimen was rigidly clamped to right-angle sections which in turn were fastened to a 15 mm thick steel tool plate, as shown in Figure 6(b). Such a heavy-duty set-up reduces rigid-body-motion of the specimen, which in turn allows for an increase in sensitivity of the shearography system (crucial for the low surface strains expected from kiss-bonds).

Thermal excitation was used, by using an infrared lamp (120 W) placed behind the specimen for approximately 30 seconds. In order to give good in-plane and out-of-plane resolution, the camera was placed directly ahead of the specimen at a distance of approximately 1.5 m, with the laser illuminating the specimen from a 45° angle. The results were obtained using 5 mm of horizontal shear. Once the specimen was heated, the interference patterns were monitored until the defects appeared (typically after 1 minute). The Defect Dtect software was used for all image capturing and processing.

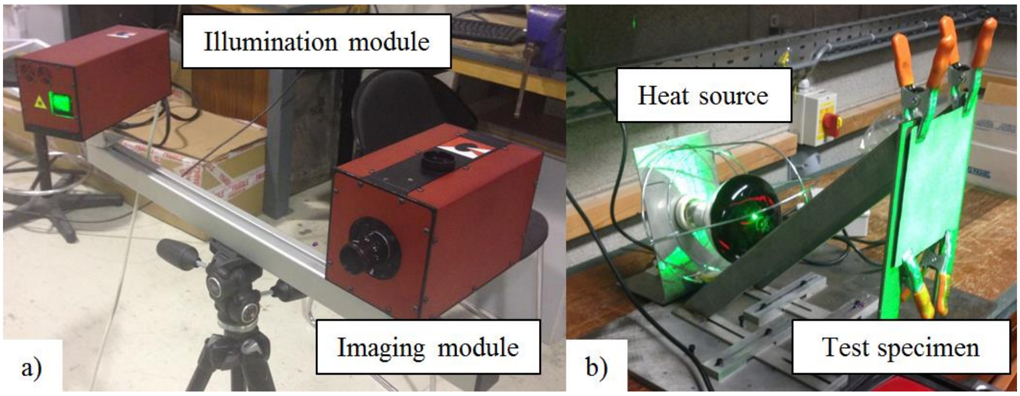

Figure 6: a) Laser Optical Engineering Laser Shearography Illumination and Imaging modules. b) Test specimen clamped into position and the location of the heat source

Using this procedure, all the defects were detectable. Figure 7 shows the images as extracted from the Defect Dtect (note: the images show approximately 110 x 110 mm of the panels). The weave of the material can make it difficult to visualise the defects but as the equipment is in operation fringes translate across the image and defect tend to 'jump out' at the operator. The defect characteristics (i.e. kiss-bond or dis-bond) were not clearly evident. While the technique may lend itself to further interrogation of the defect types, no such technique is known to the operators and thus shearography was not used to determine the defect types any further.

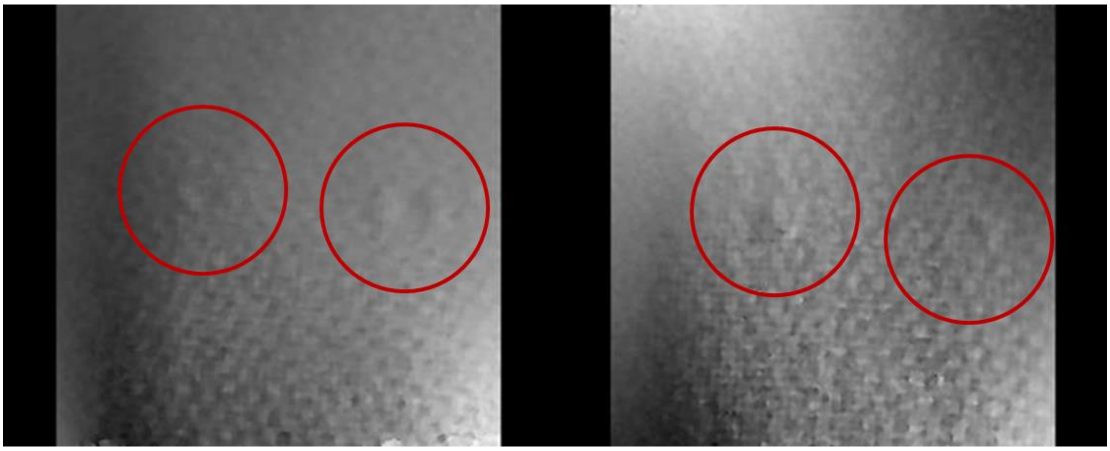

Figure 7: Typical laser shearography results. Defects are visible within the red circles.

5 DISCUSSION

The concept presented to produce kiss-bonds will be discussed in terms of its reliability, capabilities, and areas for further development. Subsequently, the performance of the NDI methods at detecting these techniques will be discussed.

5.1 Kiss-bond Manufacturing Technique

The ability of the technique developed to create kiss-bonds in a reliable fashion is of particular importance, bearing in mind the applications in NDI calibration and defect characterisation. With seven of the ten defects being identified as kiss-bonds, this technique shows excellent promise at being able to create kiss-bonds reliably. While the exact reasons behind dis-bonds being created instead of kiss-bonds are currently unknown, several possible reasons are put forward.

Aligning the defects, so that the edges line up perfectly is not a trivial task. Any slight misalignment may change the nature of the defect. For larger defects this may not be an issue but for 6x6 mm square as produced in this study, it is crucial. In future work, small needles or release film may be used to aid alignment.

The surface of the defect may be an influencing factor. The surface finish of the pre-cured areas was exceptionally flat and smooth. The use of vacuum bagging gives excellent surface quality in the pre-cured areas. However, the combination of resin-flow along with the pressure applied by the vacuum bagging results in the pre-cure area being compressed when compared to the rest of the ply. This may result in a concave section over the defect area. When two plies are stacked adjacently, these concave sections may not sit precisely into each other, giving rise to a cavity – and thus a dis-bond – being formed.

The method of using an air cavity to thermally isolate the tool-plate directly under the pre-cure area from the rest of the tool plate has resulted in excellent temperature control characteristics. However, it comes at the expense on a resin-rich 'ridge' being formed along the border of the defect. This ridge can lead to the formation of a dis-bond, where the defect surfaces are not in intimate contact. This lip was controlled by reducing the width of the cavity to 0.5mm all around. To mitigate this issue, it may be possible to use a material with a high thermal conductivity in the area under the defect, while using thermally-insulating materials for the remainder of the tool-plate. Such a material type can eliminate the need for an air-cavity, resulting in smooth and unbroken tool-plate surface.

Furthermore, one area which, it is felt, requires consideration is the effect of defect depth on the type of defect produced. The laminates used in this study were thin (8 plies thick). Following cure of the laminate at elevated temperature, it is possible that thermally induced residual stresses (following the cool-down from cure to room temperatures) may cause distortion of the laminate above and below the defect. This may cause the defect to be forced open or closed, causing a dis-bond or a kiss-bond to be produced.

5.2 Non-Destructive Inspection Assessment

Both NDI methods used were capable of detecting the defects produced. In this study, ultrasonics was also able to discern between the two defect types, while the ability of laser shearography was not explored. For the panels produced, both systems were capable of finding the defects 'blind', with no indication of the defect location, relatively easily and quickly.

In the case of ultrasonics, it is clear that it offers significant promise in detecting and assessing the defect type. However, applying the correct settings (gates, gain, etc.) required a high level of care so as to not get misleading results. This operator needs to be mindful that the back-wall echo is not a repeat echo of the defect produced (especially when the defects are in the laminate mid-plane). The results are somewhat subjective; these results may be inferred differently by another operator.

In the case of shearography, the excitation method used was relatively simple and gave good results. The shape/size of the defects were also clearer compared to ultrasonics. However, getting further information (e.g. the depth of the defect and the defect type) is more difficult using this technique. That said, shearography remains a very flexible technique that is suitable for scanning large and small areas alike, and is open to various excitation and post-processing options. Using the kiss-bond method presented in this work can lead to improved techniques to obtain further information on the defects.

5.3 Potential Future Work

Once the repeatability of the process has been demonstrated, the potential exists to perform a wide range of mechanical tests and NDI assessments which have not been possible up to now. Firstly, the effect of kiss-bonds on structural performance of a composite may be assessed. The flexibility of the technique, in terms of defect size, shape and location, allows for a comprehensive analysis on the effects of kiss-bonds, leading to a better understanding of damage growth mechanisms. Consequently, this can aid in the optimised design of damage tolerant structures. Results from any mechanical characterisation may also be utilised to validate models (e.g. finite element based) of defect growth under loading. As the method can be utilised in a variety of other composite structures, such investigations are not limited to monolithic panels. For example, the method can be used to introduce kiss-bonds into sandwich panels (defect between the core and skin materials) and bonded repairs (defect within the adhesive layer of a patch repair).

Secondly, the method has wide uses in the area of NDI for composite materials. Kiss-bonds are currently considered as the 'holy grail' of NDI in large scale composite structures (e.g. commercial jet transport aircraft, wind turbines). With a reliable and controllable method of manufacturing kiss-bonds, a comprehensive study of the exact capabilities of NDI systems at detecting kiss-bonds may be performed. Likewise, calibration panels (panels used to calibrate NDI equipment to detect certain damage types) can be manufactured using representative kiss-bonds. This is more representative than the current technique of using film insertions.

Finally, the technique may be adapted to produce weak-bonds. If kiss-bonds are classified as having no bonding across the plane of the defect, then weak bonds can be considered as similar defects but with some degree of bonding existing across the plane of the defect. By shortening the dwell time of the pre-cure phase, the defect areas are not completely cured when they are incorporated into the laminate. When the laminate is then autoclave cured, the defect continues to cure, resulting in some bonding – and thus stress-carrying capability – existing across the defect. This can lead to exciting opportunities in terms of characterising defective areas both mechanically and via NDI, as the drop in strength caused by a defect can be tuned by altering the dwell time of the pre-cure stage. This could be particularly applicable to shearography, as it uses local changes in surface strains (i.e. material stiffness) to highlight a defect, compared to the surrounding pristine material. This technique could be well placed to assess residual strength by a certain defect type (size, location, strength), using the defects developed in this study for calibration. A preliminary study has begun in this area with interesting results and it is an area that is to be pursued.

Further work has been undertaken as part of the larger study. This includes intensive interrogation of the defect surface and mechanical testing to assess if there is change in performance due to the presence of a kiss-bond. These results are to be included in a future publication.

6 CONCLUSION

Kiss-bonds are a significant issue for the composites manufacturing industry, and are effectively restricting manufacturers from pushing for lighter composite structures. In order to manufacture a composite structure that is free from kiss-bonds a reliable process of locating and assessing these defects must be developed. This paper gives an insight into a number of shortcomings with current techniques before detailing an innovative method for producing controllable and adjustable kiss-bonds by manipulating the thermosetting nature of a pre-preg laminate. The defects were created within an autoclaved monolithic laminate and assessed using NDI techniques, namely ultrasonics and laser shearography.

Ultrasonics could interrogate the defects in great detail and determined that seven of the ten defects that were created were categorised as kiss-bonds, with the remainder being categorised as dis-bonds. Shearography could locate all defects but no further interrogation could be undertaken using the particular system available to the authors.

These results are very promising and further investigation into this technique would be of great benefit to composite manufacturers of all levels. Future work includes further characterisation of the defect and an assessment of the mechanical implications it creates. Weak-bonds, defects with some degree of bonding existing across the plane of the defect, are also of interest and a preliminary study has already been undertaken.

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